PB85-110039

# Foliar Washoff of Pesticides (FWOP) Model: Development and Evaluation

(U.S.) Environmental Research Lab., Athens, GA

1984

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| 1. REPORT NO. | 2. | 3 |
|---|---|---|
| EPA-600/J-84-118 | | PB85-110039 |

| 4. TITLE AND SUBTITLE | 5. REPORT DATE |
|---|---|
| Foliar Washoff of Pesticides (FWOP) Model: Development and Evaluation (Journal Version) | 1984 |
| | 6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) | 8. PERFORMING ORGANIZATION REPORT NO. |
| C.N. Smith and R.F. Carsel | |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS | 10. PROGRAM ELEMENT NO. |
| Environmental Research Laboratory<br>U.S. Environmental Protection Agency<br>Athens GA 30613 | CBWD1A |
| | 11. CONTRACT/GRANT NO. |
| 12. SPONSORING AGENCY NAME AND ADDRESS | 13. TYPE OF REPORT AND PERIOD COVERED |
| U.S. Environmental Protection Agency--Athens GA<br>Office of Research and Development<br>Environmental Research Laboratory<br>Athens GA 30613 | Journal article |
| | 14. SPONSORING AGENCY CODE |
| | EPA/600/01 |

15. SUPPLEMENTARY NOTES
Published in J. Environ. Sci. Health. B19(3):323-342, 1984
Contact: C.N. Smith, 8-250-3565

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17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| | | |

| 18. DISTRIBUTION STATEMENT | 19. SECURITY CLASS *(This Report)* | 21. NO. OF PAGES |
|---|---|---|
| RELEASE TO PUBLIC | UNCLASSIFIED | 21 |
| | 20. SECURITY CLASS *(This page)* | 22. PRICE |
| | UNCLASSIFIED | |

EPA Form 2220-1 (9-73)

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EPA-600/J-84-118
JOURNAL ARTICLE

J. ENVIRON. SCI. HEALTH, B19(3), 323-342 (1984)

# FOLIAR WASHOFF OF PESTICIDES (FWOP) MODEL: DEVELOPMENT AND EVALUATION

Key Words: modeling, pesticides, insecticides, washoff, runoff

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## ABSTRACT

The Foliar Washoff of Pesticides (FWOP) Model was developed to provide an empirical simulation of pesticide washoff from plant leaf surfaces as influenced by rainfall amount. To evaluate the technique, simulations by the FWOP Model were compared to those by the foliar washoff algorithm of the Chemical, Runoff and Erosion from Agricultural Management Systems (CREAMS) Model. The two algorithms were linked individually to the Pesticide Runoff Simulator (PRS) for the comparison. Five years of test data from a Mississippi watershed were used to evaluate six insecticides (carbaryl, profenofos, methyl parathion, permethrin, phorate, and toxaphene).

Initially, the FWOP model was used to evaluate the relative impact of chemical distribution (foliage versus soil) on the subsequent foliar washoff and soil surface contributions to runoff losses. Results indicated that runoff losses were low if all of the insecticide was applied to the foliage whereas high losses occurred if applied only to the soil. When an assumed application was distributed between the plant and soil (i.e., 90% to foliage and 10% to soil), predicted runoff losses compared well with observed field data (<3% of the application rate).

Except for toxaphene, the FWOP model generally predicted less washoff and subsequent runoff losses than the CREAMS approach. Simulated toxaphene washoff losses were in good agreement with observed field data. Statistical comparisons of the two modeling approaches using the Kolmogorov-Smirnov test showed differences in the two cumulative frequency distributions for washoff but smaller differences for runoff. Average 5-year runoff losses, however, were greater using the CREAMS approach--by factors of 2, 3, and 3 for profenofos, methyl parathion and phorate, respectively.

Results from this study will be useful for upgrading current exposure assessment models to more accurately address foliar washoff losses of pesticides as well as for assessing the impact of foliar-applied chemicals on environmental quality.

## INTRODUCTION

The use of mathematical models as decision tools facilitates the understanding of potential risk(s) associated with exposure to chemicals in the environment. Models increasingly are being used by analysts and managers in government and industry to estimate the magnitude, frequency, duration, route of exposure, and environmental risk(s) associated with pesticide use (Falco et al., 1978; Mulkey et al., 1980). One component lacking in most of these models is a foliar washoff algorithm to account for pesticides that are removed from plant leaf surfaces by rainfall. Instead of explicitly modeling this process, most models have relied on empirical estimates based on various delivery methods.

During application, foliar-applied pesticides (particularly insecticides) are immediately partitioned or distributed between the plants, the soil (throughfall) and the atmosphere (that which is lost by drift and volatilization). The amount distributed into each compartment upon application depends on such factors as meteorological conditions, extent and nature of canopy development, plant-leaf characteristics, pesticide properties and formulations, and method of application (aerial versus ground). Once a pesticide is intercepted by a plant it may undergo several processes, including volatilization, sorption, degradation, and removal by wind and rain (Willis et al., 1980). These reactions on the plant surface influence movement of the pesticide away from the target site and may result in potential exposure to terrestrial or aquatic ecosystems.



Data relative to the influence of rainfall on pesticide removal by washoff from foliar surfaces are limited (Smith et al., 1981; Willis et al., 1980). In fact, data relating the interception of pesticides by plant foliage, removal by washoff, and contribution to surface runoff are virtually non-existent. Even so, the washoff of pesticides from foliar surfaces by rainfall can be described empirically. Thus, the development and testing of an empirical foliar washoff model fills an important gap in current pesticide exposure assessment techniques.

This paper describes the Foliar Washoff of Pesticide (FWOP) Model and defines future research needs. In particular, this paper evaluates:

- the potential contribution of foliar washoff losses to soil and runoff processes;
- the sensitivity of plant-soil distribution to runoff processes.

## MODEL THEORY AND DEVELOPMENT

Simulating the transport of pesticides applied to or intercepted by plant foliage requires the development of algorithms to represent pesticide storage, decay, and washoff from the crop cover (Beyerlein and Donigian, 1979). The amount intercepted by the foliage is assumed proportional to the extent of ground cover at the time of application (Beyerlein and Donigian, 1979; Computer Sciences Corporation, 1980; Smith et al., 1981). In conducting modeling studies, an assumption is required relative to the foliar application efficiency or the amount actually reaching the target site. The application efficiency can vary depending on whether ground or aerial equipment is

used. The amount reaching the target is then partitioned into the fraction distributed on the plant and soil. Unfortunately, field data needed to define the application efficiency as well as the distribution patterns on soil versus plant are also limited.

Several approaches (Beyerlein and Donigian, 1979; Smith et al., 1981; Willis et al., 1980) have been developed for describing the foliar washoff process for any event and generally are of the form:

$$PWO = FP \times WOC \times R \quad (1)$$

Where: PWO = pesticide washoff ($MT^{-1}$)

FP = foliage pesticide ($ML^{-2}$), i.e., kg/ha

WOC = washoff coefficient ($L^{-1}$)

R = rainfall ($LT^{-1}$)

Beyerlein and Donigian (1979) developed an equation for describing the removal of pesticides from crops by rainfall as an exponential function of the rainfall intensity. Simulations using this approach require the use of hourly rainfall records and a crop constant based on crop and pesticide properties to determine the washoff coefficient (WOC).

The CREAMS model (USDA, 1980) contains a foliar washoff algorithm for estimating the fraction of pesticide lost as a result of rainfall. The pesticide on the foliage is partitioned into dislodgeable (available for washoff) and non-dislodgeable fractions. Washoff is computed for each rainfall event from the dislodgeable fraction, less the amount decayed, after a plant washoff threshold has been reached. The washoff threshold (0.1-0.3 cm) is the amount of rainfall that a plant canopy can intercept and store prior to washoff. The pesticide dislodgeable fraction used in the CREAMS model is estimated for two pesticide classes: (1) organochlorines - less than 10%, and (2) organophosphates and other compounds - about 60%. For evaluation of the CREAMS algorithm, a dislodgeable fraction of 0.1 (organochlorine) and 0.6 (organophosphate and other) were used.

The recent development and use of synthetic pyrethroids, e.g. permethrin, with properties different from traditional pesticides (e.g., low persistence



in soil and high foliage persistence and sorption) presents a problem in determining the class into which such new compounds best fit. We chose to evaluate the pyrethroid, permethrin, as well as another new compound, profenofos (although it is an organophosphate) using values that represent both groups.

Smith et al. (1981) also have tried to explain pesticide washoff losses as a function of rainfall. A plot of the observed data is provided in Fig. 1. A linear approximation was derived from the observed data by using simple linear regression through the origin of the loss by washoff versus rainfall plot. This regression provided a WOC of approximately 8% of the residual pesticide removed as washoff per centimeter of rainfall per day. Using these data and other reported data obtained from natural rainfall events for other classes of compounds, an average or standard WOC of 10% was chosen (see Table 1). The use of a single WOC provides a simplistic means for describing the washoff process for any given pesticide regardless of its compound class. Since we anticipate that the WOC will actually be influenced by plant type, canopy structure, pesticide properties and the characteristics of individual rainfall events, and the extent of these effects is unknown due to the lack of data, additional field research is certainly needed. The linear approximation for WOC appears reasonable, however, as a first approximation from the limited available data base and is useful in this initial pesticide washoff modeling effort.

The FWOP model postulated below requires daily rainfall amounts (cm/day) and a lumped first order rate constant for foliar transformation processes (kf). The equations used to implement the FWOP model are:

$$\frac{d[FP(t)]}{dt} = -kf\ FP(t) - PWO(t) + APP(t) \quad (2)$$

Where: $\frac{d[FP(t)]}{dt}$ = rate of change of pesticide on foliage

kf = first order degradation rate constant on the foliage ($T^{-1}$)

APP(t) = application rate ($MT^{-1}$)

and: $$PWO(t) = FP(t) \times WOC \times R(t) \quad (3)$$

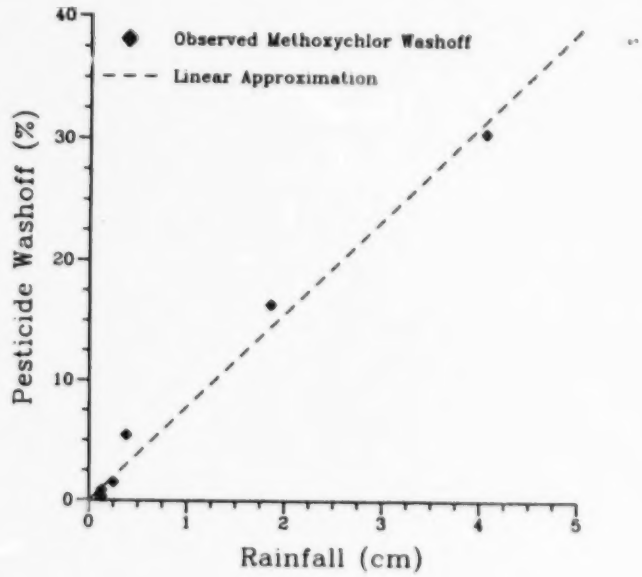


Figure 1
Observed Methoxychlor Washoff from Soybean Crop and the Linear approximation of Washoff-Rainfall Relationship

TABLE 1
Calculated Pesticide Washoff Extraction Coefficient (WOC) from Three Experiments

| Pesticide | Crop Type | Days After Application | Rainfall (cm) | Pesticide Washoff per Rainfall Volume(%) |
|---|---|---|---|---|
| Parathion[a] | Citrus | 48 | 6.4 | 10.2 |
| | | 22 | 6.4 | 10.9 |
| Dimilin[a] | Cotton | 14 | 7.6 | 9.2 |
| Methoxy-chlor[b] | Soybeans | 2-21 | 0.13-4.04 | 8 ± 4% |

[a] Willis et al., 1980.

[b] Smith et al., 1981.



where: $PWO(t)$ = pesticide washoff ($MT^{-1}$)

$FP(t)$ = foliage pesticide ($ML^{-2}$)

$WOC$ = washoff coefficient ($L^{-1}$)

$R$ = rainfall ($LT^{-1}$)

The above mass balance equation cannot be solved analytically in closed-form because rainfall is variable in time. Also, the chemical is applied on specific days and not continuously over time. The equations therefore, must be solved numerically as part of a continuous simulation model.

## MODEL EVALUATION

One objective of this study was to determine the impact of foliar washoff and application distribution on subsequent runoff losses. This is a key question because most insecticides are foliar-applied and yet exposure assessment modeling studies are being done without knowledge of the real impact of application distribution and foliar washoff behavior. This impact was evaluated by testing three alternative assumptions relative to the distribution of the pesticide immediately following pesticide application: (1) that 99% of the applied material is intercepted by the plant foliage and the compound becomes sorbed to the plant and unavailable for washoff, (2) that all the material is applied to the soil with no interception by the plant, and (3) that the material is distributed between the plant foliage (90%) and the surface soil (10%).

These three scenarios were evaluated by coupling the PWOP with the Pesticide Runoff Simulator (PRS) (Computer Sciences Corporation, 1980). In the PRS model, the hydrology component is described by a curve number technique (Computer Sciences Corporation, 1980), the erosion component is based on the modified universal soil loss equation (MUSLE) (Williams and Berndt, 1977), and the chemical transport component is a modification of the CREAMS approach (USDA, 1980). Six insecticides were used in the simulations: carbaryl, 1-naphthyl N-methylcarbamate; profenofos, O-(4-bromo-2-chlorophenyl)-O-ethyl S-propyl phosphorothioate; methyl parathion, O,O-dimethyl-O-p-nitrophenyl

phosphorothioate; permethrin, 3-(phenoxyphenyl) methyl-3-(2,2 dichloroethenyl)-2,2-dimethyl cyclopropanecarboxylate; phorate, O,O-diethyl S-[(ethylthio)-methyl] phosphorodithioate; and toxaphene, a chlorinated camphene. The selected compounds represent carbamate, organophosphorous, organochlorine, and synthetic pyrethroid classes. The insecticides selected have varying application rates, foliar and soil decay rates, and soil distribution coefficients (Table 2).

Six simulated applications at weekly intervals starting in early August for each of 5 years (1971-1975) was assumed for the evaluations. The senario field site chosen for the model evaluations was an actual 15.6 ha (38.5 ac) watershed planted in cotton (Gossypium hirsutum L.) in the Yazoo River Basin in Mississippi. Data on precipitation, runoff, sediment yield, pesticide yield (toxaphene), plant canopy development, and field-site characteristics were available (Willis et al., 1976). Model performance testing of three runoff loading models (Lorber and Mulkey, 1982) as well as exposure assessment studies (Falco et al., 1978; Mulkey at al., 1980) had already been performed at this study site. In order to expand the range of pesticide properties used in the model test, phorate was included as a pesticide possessing a low $K_D$ (9.4) and low $K_s$ (first order degradation rate constant in soil) of 0.0069 days$^{-1}$. Phorate is not normally foliar-applied because it is a granular formulation intended for soil incorporation. Therefore, the modeling results presented in this paper for phorate must be interpreted as a surrogate foliar-applied compound with properties similar to phorate.

The second objective was to conduct an evaluation of the FWOP model that included three tests: (1) performance as compared with the similar CREAMS approach for foliar washoff, (2) comparison of predicted total runoff loadings produced by the PRS model using the two foliar washoff algorithms, and 3) sensitivity analysis. (Hereafter the FWOP model algorithm will be designated Model A and the CREAMS algorithm Model B.) Comparisons



TABLE 2
Application Rate and Transformation and Transport Properties of Selected Insecticides

| Insecticide | Common Name[e] | Application Rate[a] (kg/ha) | Lumped First Order Rate Constant[d] (days$^{-1}$) Foliage, $K_F$ | Soil, $K_S$ | Soil Distribution Coefficient[d] ($K_D$, ml/g) | Solubility[e] (ug/ml) |
|---|---|---|---|---|---|---|
| Sevin | Carbaryl | 1.68 | 0.1019 | 0.0788 | 2.5 | 40 |
| Curacron | Profenofos | 1.12 | 0.3465[b] | 0.0693[b] | 55[b] | 20 |
| Methyl Parathion | Methyl Parathion | 0.28 | 0.231 | 0.0165 | 13.3 | 55-60 |
| Permethrin | Permethrin | 0.56 | 0.0198 | 0.0396 | 233[f] | 4 |
| Thimet | Phorate | 3.36 | 0.3465 | 0.0069 | 9.4 | 50 |
| Toxaphene | Toxaphene | 0.63 | 0.1083 | 0.0046 | 6000 | 3[f] |

[a] University of Georgia, 1981.
[b] Larry Ballantine, Personal Communication Ciba-Geigy Corp., Greensboro, NC, 1982.
[c] Ron Cook, Personal Communication, FMC Corp., Middleport, NY, 1982.
[d] USDA, 1980 and/or estimated.
[e] Anon., 1981.
[f] British Corp Protection Council, 1968.

of model predictions were based on annual and 5-year averages for the six insecticides noted in Table 2. The use of 5-year simulations enables sufficient data generation for analysis and allows influence of rainfall patterns to be evaluated for annual variability. The Kolmogorov-Smirnov test (Siegel, 1956) was used to determine whether any differences occur within distributions from which the sample populations were drawn and to identify differences in location (central tendency), dispersion, or skewness.

## RESULTS AND DISCUSSION

The PRS model was calibrated with observed field data for toxaphene and a series of three simulations was performed using the FWOP model according to the three assumptions stated earlier. Simulation results are presented in Table 3. The calculated amount of pesticide lost in runoff (% of total applied) is low when all is assumed to be applied to plant foliage (test 1) and high (test 2) when all is applied to the bare soil. This is especially true for methyl

TABLE 3
Simulated Runoff Loss (5-Year Average) of Six Insecticides with Various Plant/Soil Distributions (FWOP with PRS)

| Pesticide | Application Distribution: Plant (Test 1) (kg/ha) | (% of Applied) | Soil (Test 2) (kg/ha) | (% of Applied) | Plant and Soil (Test 3) (kg/ha) | (% of Applied) |
|---|---|---|---|---|---|---|
| Carbaryl | 0.001 | 0.01 | 0.366 | 4.54 | 0.251 | 3.13 |
| Profenofos | 0.001 | 0.02 | 0.056 | 1.00 | 0.011 | 0.20 |
| Methyl-Parathion | 0.001 | 0.08 | 0.119 | 8.92 | 0.021 | 1.57 |
| Permethrin | 0.001 | 0.04 | 0.009 | 0.38 | 0.010 | 0.40 |
| Phorate | 0.002 | 0.01 | 2.59 | 16.05 | 0.307 | 1.90 |
| Toxaphene | 0.001 | 0.01 | 0.209 | 6.10 | 0.098 | 2.99 |

parathion, phorate, and toxaphene relative to actual field data for carbaryl, methyl parathion and toxaphene reported by Wauchope (1978). When the applied pesticide is distributed (test 3) between the plant surface (90%) and the soil (10%) as throughfall, calculated runoff losses are <3% of the total application. This agrees with findings from observed field runoff studies (Carroll et al., 1981; Johnson and Baker, 1982; Smith et al., 1978; Wauchope, 1978). Permethrin runoff losses are similar whether applied on the soil (test 2) or distributed between the plant and soil (test 3). The probable reason for similar runoff results is that permethrin is very persistent on the foliage (half-life 35 days); therefore, a large fraction is allowed to wash off and become part of the runoff loss. In other comparisons of test 2 and test 3, essentially no apparent difference was observed for carbaryl runoff loss; whereas for profenofos, methyl parathion, phorate and toxaphene, runoff loss was greater by a factor of 5, 4, 8, and 2, respectively, when all was applied to the soil. The results of these simulation analyses clearly show the importance of the initial distribution of applied pesticide on both the plant foliage and soil. They also show



that washoff from plant foliage cannot be ignored when conducting pesticide exposure assessment studies on foliar applied pesticides.

Model B simulations were made using the recommended dislodgeable fraction values (organochlorine 0.1, other compounds 0.6). Permethrin and profenofos were evaluated using both dislodgeable fraction values as a possible range for these compounds. The simulated 5-year foliar washoff losses are shown in Table 4. The difference between the amount applied to foliage and the effective amount applied to the target site represents the mass that reaches the soil upon application. The estimated amount distributed to the soil upon application is much less than the predicted foliar washoff losses. The total foliar washoff predictions by Model B are consistently greater than Model A except for toxaphene, profenofos, and permethrin. For some compounds, calculated washoff losses from the foliage were as high as 50 to 90% as shown for permethrin. The predicted toxaphene washoff losses by both models were in agreement with observed washoff using a multiple-intensity rainfall simulator (Willis et al., 1982).

Model results were evaluated by the Kolmogorov-Smirnov two-sample test (Siegel, 1956) using daily values of foliar washoff predicted for the 5-year simulation. Graphical analyses for methyl parathion, permethrin and toxaphene are shown in Figures 2-6. Statistically significant differences (i.e., the maximum absolute difference (K) is greater than critical values [K0]) were observed for all pesticides except toxaphene when comparing Model A versus Model B (WOC = 0.6). There were no statistically significant differences for profenofos and permethrin when Model B (WOC = 0.1) was used (i.e., K<K0).

The results indicate there are differences in the two techniques for modeling foliar washoff, which includes the assumed assignment of a dislodgeable fraction or washoff coefficient value for pyrethroid type compounds. The lack of extensive field data on foliar washoff precludes a thorough assessment of the overall accuracy or reliability of the two models.

The models were evaluated further by comparing predicted average annual and 5-year (1971-1975) runoff losses using the two approaches with the USS

TABLE 4
Comparative 5-Year Simulations of Foliar Washoff Pesticide Losses

| Pesticide | Year | Effective Amount Applied/Year (kg/ha) | Foliar Fraction (kg/ha) | Total Foliar Washoff (kg/ha) | | | % Washoff from Foliar Fraction | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Model A* | Model B+ Dislodgeable Fraction | | Model A | Model B Dislodgeable Fraction | |
| | | | | | 0.10 | 0.60 | | 0.1 | 0.60 |
| Carbaryl | 1971 | 8.57 | 8.01 | 1.50 | -- | 5.08 | 19 | -- | 63 |
| | 1972 | 8.57 | 8.01 | 0.94 | -- | 3.24 | 12 | -- | 40 |
| | 1973 | 8.57 | 8.01 | 1.62 | -- | 4.58 | 20 | -- | 57 |
| | 1974 | 8.57 | 8.01 | 2.62 | -- | 5.88 | 33 | -- | 73 |
| | 1975 | 8.57 | 8.01 | 1.79 | -- | 4.59 | 22 | -- | 57 |
| Profenofos | 1971 | 5.43 | 5.37 | 0.47 | 0.45 | 2.04 | 9 | 8 | 38 |
| | 1972 | 5.43 | 5.37 | 0.14 | 0.12 | 0.63 | 3 | 2 | 12 |
| | 1973 | 5.43 | 5.37 | 0.43 | 0.37 | 1.49 | 8 | 7 | 28 |
| | 1974 | 5.43 | 5.37 | 0.69 | 0.65 | 2.69 | 13 | 12 | 50 |
| | 1975 | 5.43 | 5.37 | 0.42 | 0.31 | 1.42 | 8 | 6 | 27 |
| Methyl Parathion | 1971 | 1.43 | 1.34 | 0.15 | -- | 0.61 | 11 | -- | 46 |
| | 1972 | 1.43 | 1.34 | 0.06 | -- | 0.26 | 5 | -- | 20 |
| | 1973 | 1.43 | 1.34 | 0.14 | -- | 0.49 | 11 | -- | 37 |
| | 1974 | 1.43 | 1.34 | 0.24 | -- | 0.77 | 18 | -- | 58 |
| | 1975 | 1.43 | 1.34 | 0.14 | -- | 0.48 | 11 | -- | 36 |
| Permethrin | 1971 | 2.86 | 2.67 | 1.37 | 1.34 | 2.38 | 51 | 50 | 89 |
| | 1972 | 2.86 | 2.67 | 1.27 | 1.08 | 2.14 | 48 | 40 | 80 |
| | 1973 | 2.86 | 2.67 | 1.39 | 1.37 | 2.34 | 52 | 51 | 88 |
| | 1974 | 2.86 | 2.67 | 1.94 | 1.62 | 2.48 | 73 | 61 | 93 |
| | 1975 | 2.86 | 2.67 | 1.58 | 1.30 | 2.34 | 59 | 49 | 88 |
| Phorate | 1971 | 17.14 | 16.10 | 1.42 | -- | 6.10 | 9 | -- | 38 |
| | 1972 | 17.14 | 16.10 | 0.44 | -- | 1.89 | 3 | -- | 12 |
| | 1973 | 17.14 | 16.10 | 1.29 | -- | 4.46 | 8 | -- | 28 |
| | 1974 | 17.14 | 16.10 | 2.07 | -- | 8.06 | 13 | -- | 50 |
| | 1975 | 17.14 | 16.10 | 1.25 | -- | 4.24 | 8 | -- | 27 |
| Toxaphene | 1971 | 3.20 | 3.00 | 0.44 | 0.42 | -- | 15 | 14 | -- |
| | 1972 | 3.20 | 3.00 | 0.25 | 0.42 | -- | 8 | 7 | -- |
| | 1973 | 3.20 | 3.00 | 0.40 | 0.40 | -- | 13 | 13 | -- |
| | 1974 | 3.20 | 3.00 | 0.88 | 0.74 | -- | 29 | 25 | -- |
| | 1975 | 3.20 | 3.00 | 0.49 | 0.40 | -- | 16 | 13 | -- |

* Model A: FWOP Model

+ Model B: Foliar washoff component of CREAMS

model, Table 5. Note that annual runoff losses are much less than foliar washoff losses (Table 5 versus Table 4). The results indicate differences in the total pesticide loss for both annual and 5-year averages for carbaryl, profenofos, methyl parathion, and phorate when comparing Model A versus Model B (WOC = 0.6). Again, Model B generally predicted higher runoff losses than Model A.



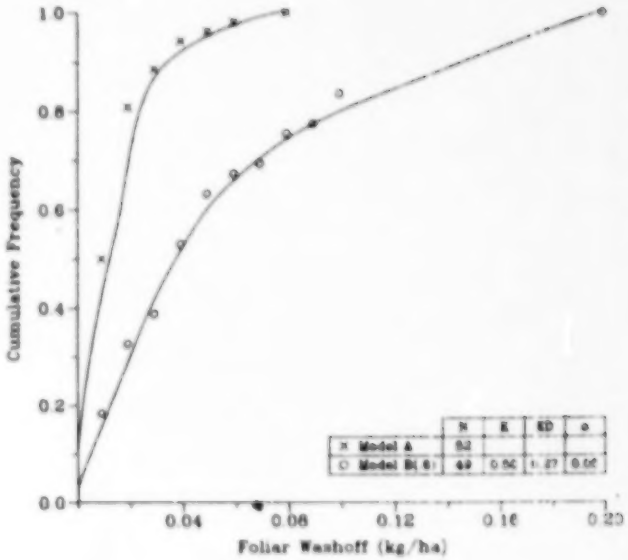


Figure 2
Cumulative Frequency of Methyl Parathion Washoff (K-S Test Parameters: N = number of data points, K = maximum absolute difference, KD = critical value, α = level of significance)

No apparent differences for annual and 5-year average occur for profenofos and toxaphene when Model A versus Model B (WOC = 0.1) are compared. No differences in total runoff loss between the models were exhibited for permethrin. Indeed, the results for permethrin suggest that the long foliar half-life (35 days) contributes to a high washoff fraction for both models (5-year average)--runoff loss for permethrin is low, however. These results agree with findings of Carroll et al. (1981) where a wide range of rainfall and runoff conditions produced losses of <1% of that applied. The high soil distribution coefficient ($K_D$ = 633) suggests that most of the chemical would be removed from the field by sediment transport during the erosion process. The low soil persistence (half-life 17 days) would not allow the chemical to be present for an extended period of time, thus the small total runoff loss and low sensitivity to foliar washoff by either algorithm or WOC value.

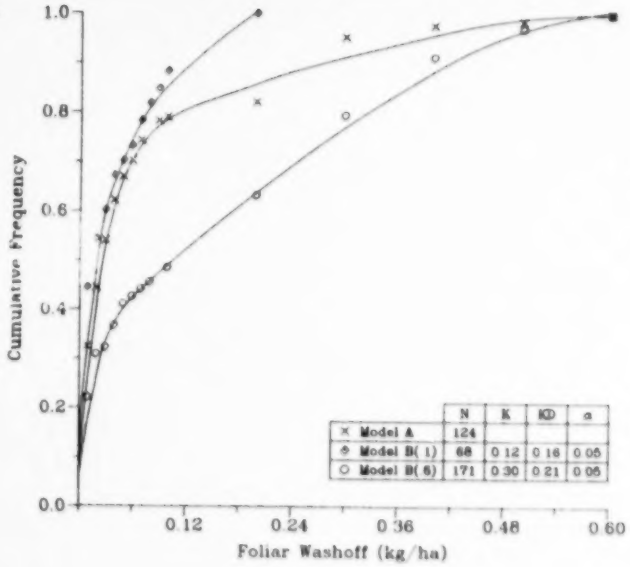


Figure 3
Cumulative Frequency of Permethrin Washoff (K-S Test Parameters: N = number of data points, K = maximum absolute difference, KD = critical value, α = level of significance)

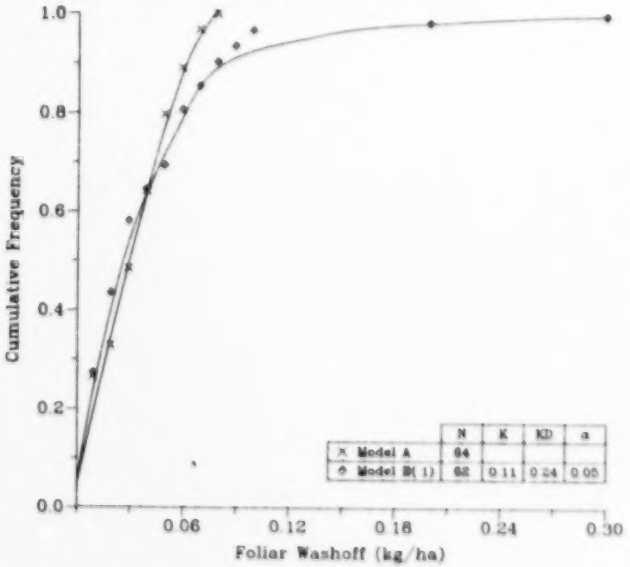


Figure 4
Cumulative Frequency of Toxaphene Washoff (K-S Test Parameters: N = number of data points, K = maximum absolute difference, KD = critical value, α = level of significance)



TABLE 5
Comparative 5-Year Simulations of Pesticide Losses by Runoff

| Pesticide | Year | Annual Runoff Loss (kg/ha) | | | Average 5-Year Runoff Loss(% of applied) | | |
|---|---|---|---|---|---|---|---|
| | | Model A | Model B Dislodgeable Fraction | | Model A | Model B Dislodgeable Fraction | |
| | | | 0.1 | 0.6 | | 0.1 | 0.6 |
| Carbaryl | 1971 | 0.174 | -- | 0.262 | 3.13 | -- | 4.34 |
| | 1972 | 0.010 | -- | 0.027 | | | |
| | 1973 | 0.032 | -- | 0.075 | | | |
| | 1974 | 0.791 | -- | 0.945 | | | |
| | 1975 | 0.248 | -- | 0.401 | | | |
| Profenofos | 1971 | 0.007 | 0.004 | 0.018 | 0.20 | 0.13 | 0.69 |
| | 1972 | 0.001 | 0.001 | 0.001 | | | |
| | 1973 | 0.002 | 0.001 | 0.004 | | | |
| | 1974 | 0.036 | 0.023 | 0.088 | | | |
| | 1975 | 0.008 | 0.004 | 0.019 | | | |
| Methyl Parathion | 1971 | 0.015 | -- | 0.046 | 1.57 | -- | 4.50 |
| | 1972 | 0.008 | -- | 0.029 | | | |
| | 1973 | 0.011 | -- | 0.034 | | | |
| | 1974 | 0.055 | -- | 0.150 | | | |
| | 1975 | 0.017 | -- | 0.044 | | | |
| Permethrin | 1971 | 0.006 | 0.004 | 0.004 | 0.26 | 0.26 | 0.30 |
| | 1972 | 0.010 | 0.009 | 0.006 | | | |
| | 1973 | 0.008 | 0.007 | 0.004 | | | |
| | 1974 | 0.020 | 0.015 | 0.021 | | | |
| | 1975 | 0.004 | 0.003 | 0.004 | | | |
| Phorate | 1971 | 0.252 | -- | 0.021 | 1.90 | -- | 6.20 |
| | 1972 | 0.122 | -- | 0.489 | | | |
| | 1973 | 0.194 | -- | .610 | | | |
| | 1974 | 0.726 | -- | 2.351 | | | |
| | 1975 | 0.242 | -- | 0.893 | | | |
| Toxaphene | 1971 | 0.021 | 0.921 | -- | 2.99 | 2.29 | -- |
| | 1972 | 0.088 | 0.087 | -- | | | |
| | 1973 | 0.087 | 0.085 | -- | | | |
| | 1974 | 0.095 | 0.093 | -- | | | |
| | 1975 | 0.158 | 0.148 | -- | | | |

Toxaphene is also highly partitioned to soil ($K_D$ = 400) and highly persistent (soil half-life 150 days). These properties indicate that the residue reaching or remaining in the soil would be available for runoff over a longer period of time, thus a higher total loss (3%), even though it has a shorter foliar half-life (6.4 days) and a smaller washoff fraction than

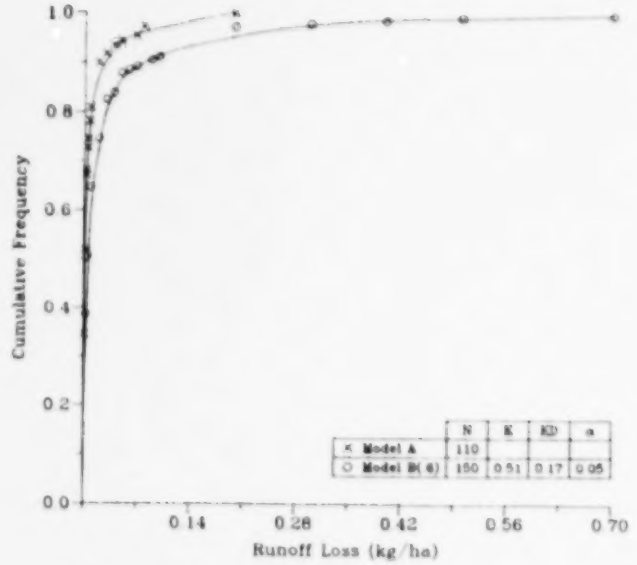


Figure 5
Cumulative Frequency of Phorate Runoff ( K-S Test Parameters
N = number of data points, K = maximum absolute difference,
KD = critical value, α = level of significance)

permethrin. The results for carbaryl, profenofos (except for Model B, where WOC = 0.1), methyl parathion, and phorate indicate that foliar washoff estimates are sensitive to the various combinations of foliar half-life, soil half-life, and distribution coefficient. Average 5-year runoff loss estimates differ by factors of 2, 3, and 3 for profenofos, methyl parathion and phorate, respectively.

The simulated 5-year runoff estimates generated by the two models were again analyzed by the Kolmogorov-Smirnov two-sample test. Except for phorate, there were no statistically significant differences for any of the pesticide runoff estimates (Figure 5). Total annual runoff losses can vary, however, as shown in Table 5. Runoff data from a similar study on foliar applied carbofuran produced higher residues in runoff water than soil applied granular formulation (National Research Council of Canada, 1979). Given that the general chemical



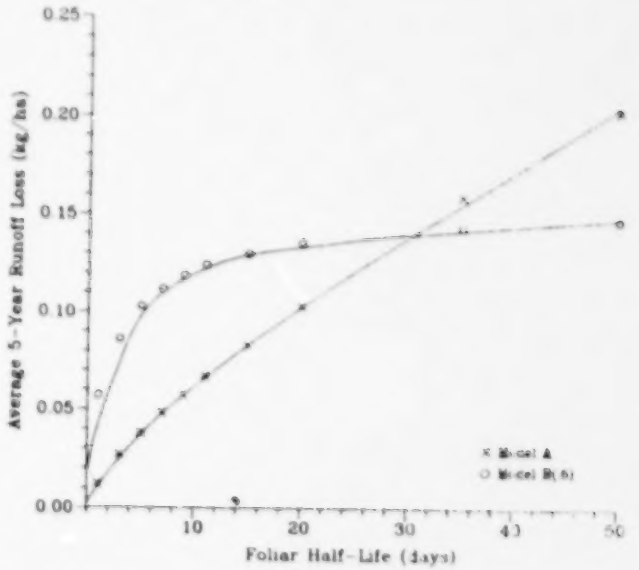


Figure 6
Model Sensitivity of Foliar Persistence to Profenofos Runoff Loss
(KD = 15)

properties associated with carbofuran are similar to phorate (low $K_D$, high $K_S$) the carbofuran test results support the model results here relative to phorate. Additional model testing, however, is needed with compounds of similar properties.

A final comparison of the two models was performed by sensitivity testing of the two algorithms using profenofos as the test compound. The test consisted of varying the foliar half-life and the distribution coefficient, while holding the soil dissipation rate (0.0693 $days^{-1}$) and application rate (1.12 kg/ha) constant. The response of the two models varied with Model b (WOC = 0.6) having little sensitivity to runoff loss beyond a foliar half-life of 20 days for all ranges of soil distribution coefficients ($K_D$ = 5, 15, 30, 55 and 550). Both models converged at a foliar half-life of about 20 days with greater differences appearing at $K_D$ of 15 (see Figure 6). The

response to runoff increases for Model A as the foliar half-life increases. At a foliar half-life of 1.0 day there is a factor of 3.0 difference, whereas at 50.0 days a factor of >1 exists. The smallest differences (less than 1.0) occur between foliar half-lives of 20-35 days. For all distribution coefficients evaluated, the largest differences occur at a foliar half-life of 1.0 day. The sensitivity analysis performed does not provide a unique solution to model evaluation; rather the test provides insight into differences between the two models for chemicals that possess similar properties.

In summary, the empirically based FWOP model for describing foliar washoff appears to be consistent with available data (daily rainfall) and is simpler in form than other models because it eliminates one variable--the washoff coefficient. The results of this analysis clearly show that foliar processes (fate and washoff) are substantial factors in contributing to potential terrestrial and aquatic environmental problems and therefore must be included in current exposure assessment simulation techniques. Certainly, further field testing of this approach is needed. Interactions among foliar processes, soil processes and runoff are sufficently complex as to preclude simple "rules of thumb," i.e., we must continue to model the system via continuous simulation.

Some key areas of research needed to extend current knowledge relative to pesticide behavior on foliar surfaces are:

- Additional field and/or greenhouse studies to develop and extend the present (limited) data base, i.e., relate the interception of pesticides by plant foliage, removal by washoff and its contribution to surface runoff.
- Studies to better define the application distribution on plant foliage and the amount that reaches the soil upon application as through-fall as well as to quantify drift losses as they affect target application rates.
- Studies to define plant-chemical interaction as it relates to washoff, sorption, photochemical degradation and volatilization.



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Received: August 15,1983